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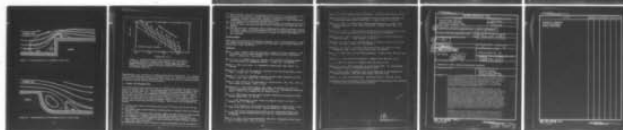
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## ATMOSPHERIC DISPERSION CHARACTERISTICS IN COASTAL ENVIRONMENTS

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### ABSTRACT

Proposed construction of offshore facilities such as nuclear-power plants, airports, and other structures which are potential emitters of pollutants necessitate consideration of atmospheric diffusion and analysis of the feasibility of such structures from the meteorological point of view. The potentially harmful nature of the radioactive materials involved dictates that even small quantities be treated with respect. Special attention must be given to design criteria in locations where hurricanes (typhoons), storm surges, tsunamis, waterspouts, or other catastrophic meteorological and oceanographic phenomena may occur.

The movement of air pollutants is governed primarily by wind systems. In coastal zones influenced by land- and sea-breeze systems, at least two inversion layers exist: the mesoscale subsidence inversion and inversion associated with the internal boundary layer. Under onshore wind conditions (whether sea breeze or general gradient winds), an internal boundary layer occurs in the coastal zone owing to aerodynamic roughness as the wind crosses the sea and land interface. Therefore, plume trapping in the coastal boundary layer during onshore winds is pronounced and causes serious degradation of air quality. Thus, from an air-pollution point of view, there is no advantage to locating a power plant or similar structure offshore because onshore airflow will bring the pollutants to the coast. Furthermore, serious consideration should be given to site selection in coastal regions located east of the subtropical high-pressure region centered between 30° and 40° latitude because subsiding air produces inversions and light winds in addition to sea breeze effects. Cities in such areas are in the worst possible locations from the standpoint of vulnerability to pollution. Location of plants in these coastal areas should by all means be avoided.

Nevertheless, there are some areas along continental and island coasts which may be suitable for power plant or airport location. Major criteria are the following: (1) Offshore winds should be prevalent during most of the year, particularly during the summer; (2) the upwind coastal region should be relatively flat in order to avoid a mesoscale turbulent vortex; (3) offshore bottom slope should be gentle and bathymetrically uniform to attenuate storm surges and minimize wave effects.

### 1. INTRODUCTION

In order to reduce the air-pollution concentration over land, it has been proposed that power plants (nuclear and coal-fired), airports, and other facilities be constructed offshore. The problem is complicated, however, by the fact that the movement of air pollutants is governed primarily by coastal wind systems and onshore wind brings pollutants to the coast. According to Slade (1968), the total amount of debris released during routine atomic processes and considered possible from accidents is minuscule when compared to the amount of pollutants produced throughout the world by combustion. Radioactive materials are extraordinarily poisonous (Slade, 1968), however, and require that even small quantities be given utmost attention.

From the standpoint of aerodynamic characteristics in the atmospheric boundary



(friction) layer, the coastal region is a special type of transitional zone in which the airflow continuously readjusts itself to a new set of boundary conditions as it crosses the shoreline. The line of separation between land and water constitutes a discontinuity in terms of the roughness of the underlying surface, as well as of heat, moisture, and aerosol distribution. It is the purpose of this paper to review and summarize the state of knowledge of atmospheric dispersion characteristics in the coastal zone. Particular emphasis is given to mesoscale meteorological considerations in site selection. This scale of atmospheric motion controls the major movement and dispersion of pollutants across the air-sea-land interface.

## 2. METEOROLOGICAL ELEMENTS

Before atmospheric dispersion characteristics in the coastal zone are discussed, a review of the existing diffusion formulae is in order. The diffusion of pollution downwind from an elevated continuous point source is often represented by the following expression (see, e.g., World Meteorological Organization, 1972):

$$u\chi/Q = \frac{1}{\pi S_y S_z} \exp(-y^2/2S_y^2) \left[ \exp - \frac{(z-h)^2}{2S_z^2} + \exp - \frac{(z+h)^2}{2S_z^2} \right] \quad (1)$$

where  $u$  is the mean horizontal wind speed (m/sec) (the  $x$ -axis is oriented in the direction of the wind),  $\chi$  is the ground-level concentration (units/m<sup>3</sup>),  $Q$  is the source strength (units/sec),  $S_y, S_z$  are the standard deviations of the distributions of concentrations in the  $y$  (cross-wind) and  $z$  (vertical) directions and are functions of downwind distance  $x$ , and  $h$  is the effective source emission height (m).

This model is based on several main assumptions. Among them are steady-state conditions and homogeneous flow, i.e., no time and space changes in wind (or turbulence). Equivalent expressions have been developed for instantaneous point sources and line sources (e.g., Slade, 1968).

Another important meteorological parameter is the height of the surface layer within which pollutants are mixed by turbulence and diffusion. If the mixing height is denoted by  $D$ , the concentration is given by the equation

$$\chi = \frac{Q}{\sqrt{2\pi} uD S_y} \exp\left(-\frac{y^2}{2S_y^2}\right) \quad (2)$$

or

$$\chi \propto \frac{1}{uD} \quad (2a)$$

where  $uD$  is the ventilation factor.

Utilization of Eqs. (1) and (2) is limited in the coastal zone, largely because of the difficulty of finding uniform fetches and steady-state conditions. Diurnal variation in the value of  $D$  and in the vector wind is present even when regional pressure patterns are constant (e.g., Holzworth, 1972). Secondly, mesoscale meteorological circulations (sea breezes, valley flows, etc.) and diurnal wind reversals (e.g., Hsu, 1970) occur in many parts of the world (e.g., Defant, 1951; Jehn, 1973). Finally, migrating anticyclones and cyclones often result in non-steady-state conditions. Therefore, the coastal zone requires special consideration, particularly with respect to atmospheric dispersion characteristics.



### 3. DISPERSION CHARACTERISTICS IN THE COASTAL ZONE

#### 3.1. Scales of Atmospheric Phenomena

Weather phenomena occur on a very wide range of time and space scales, as shown in Figure 1. However, the most important scale affecting atmospheric dispersion is in the range of 1 to 100 km and of 1 hour to 2 days. This is the region of the meso- and synoptic-scales. The diurnal wind system in a given region dictates the bulk movement and diffusion in that region.

The vertical scale of air movement over flat land is shown in Figure 2. In the surface layer, which has been found to extend to 150 m above the surface (Carl et al., 1973), the effects of the earth's rotation (Coriolis force) are relatively small in comparison with effects which arise from the surface itself. The theoretical geostrophic wind is attained between 500 and 1,000 m, and above this height, in the free atmosphere, friction may be ignored. The geostrophic approximation is based on the assumption that the air adjusts its speed to maintain a balance between the pressure gradient and the Coriolis force. Between the surface layer and the free atmosphere is the transitional region, where surface friction, density gradient, and Coriolis force are important.

The type of atmospheric layering, such as shown in Figure 2, to be considered will depend on the effective source emission height, which is the sum of the physical stack height and the plume rise. Some examples are given in later sections.

#### 3.2. Synoptic Subsidence Inversion

In meteorology, the term "synoptic" refers to the use of meteorological data obtained simultaneously over a wide area for the purpose of presenting a comprehensive and almost instantaneous picture of the state of the atmosphere (see, e.g., Figure 3). Note that the wind around a high-pressure cell or anticyclone is clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. If a coastal city is located on the eastern side of the high, as in the case of Los Angeles, California, the upper air coming from the colder region (from the northwest) will have a descending motion because it is colder than the surrounding air. The subsiding air warms and dries as it sinks, becoming warmer and drier than the air near the surface. Thus temperature increase with height occurs. This is the inversion, as opposed to the normal condition, where temperature decreases with height.

An example of synoptic subsidence inversion is shown in Figure 4. Up to about 350 m the temperature decreases with height normally, but above that height a thick inversion layer is present which acts as a lid on upward mixing of contaminants introduced from below. The most persistent and most nearly stationary anticyclones are the subtropical highs. These are centered between 30° and 40° latitude over the eastern portions of the oceans throughout the warm half of the year (cf. Fig. 3). The divergent subsiding air east of the centers produces inversions and light winds along all subtropical west coasts of continents, and if there are sufficient sources of pollution the result is persistent high concentrations of smog. Cities in such areas (Casablanca, Capetown, Lima, and Los Angeles) have developed in the worst possible locations from the standpoint of vulnerability to smog (Neiburger, 1969).

#### 3.3. Diurnal and Local Wind Effects

Diurnal wind changes are most pronounced near coastlines, particularly in the tropics. The land-sea breeze is the most familiar local circulation. Estoque (1962) has presented numerically derived models of the sea breeze according to the prevailing synoptic situation. McPherson (1970) expanded Estoque's model to three dimensions, including effects of bays. On the basis of observations of the Texas Gulf Coast

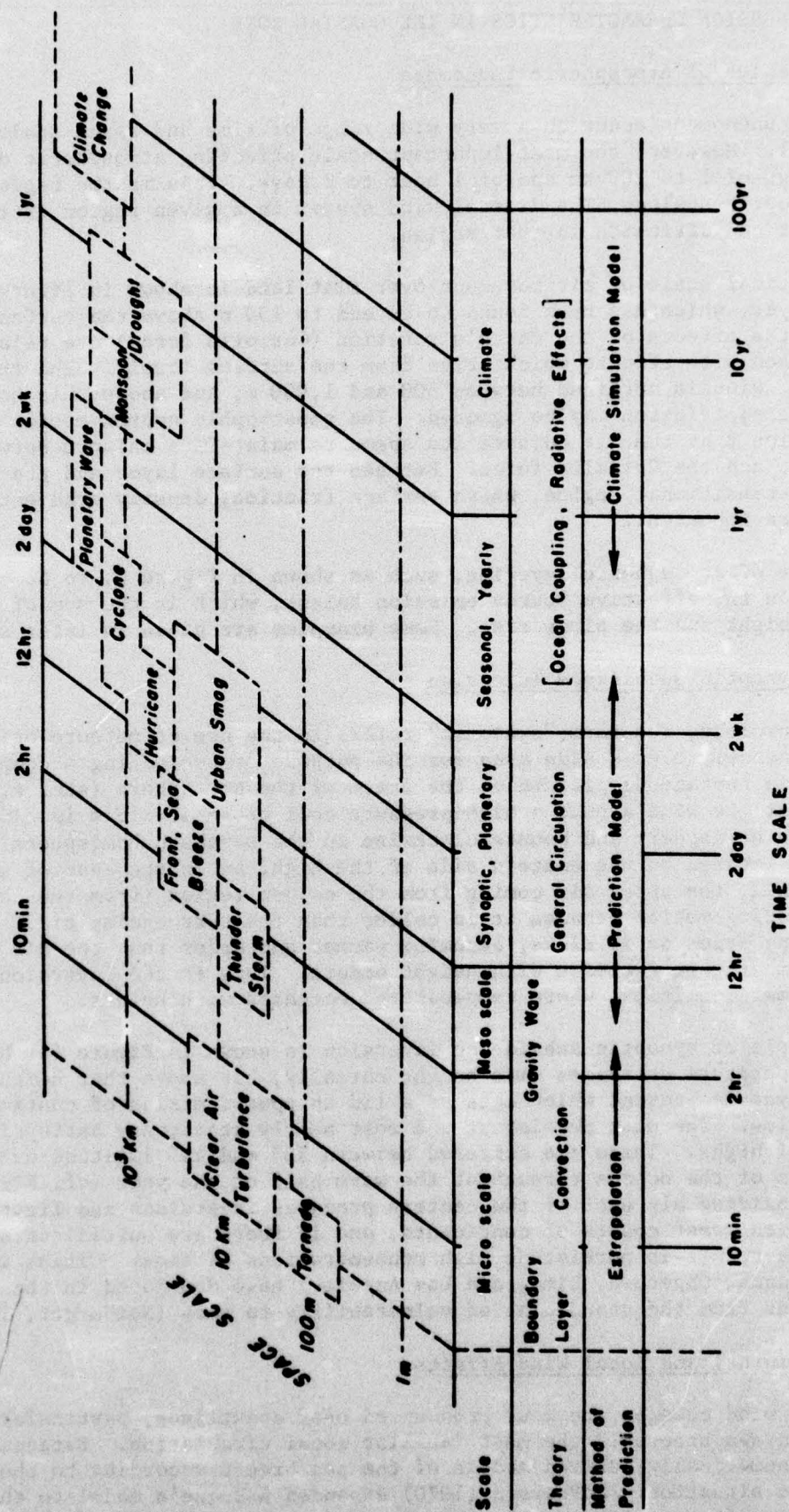


Figure 1. Time and space scales of atmospheric phenomena and their prediction (Fleagle, 1971).



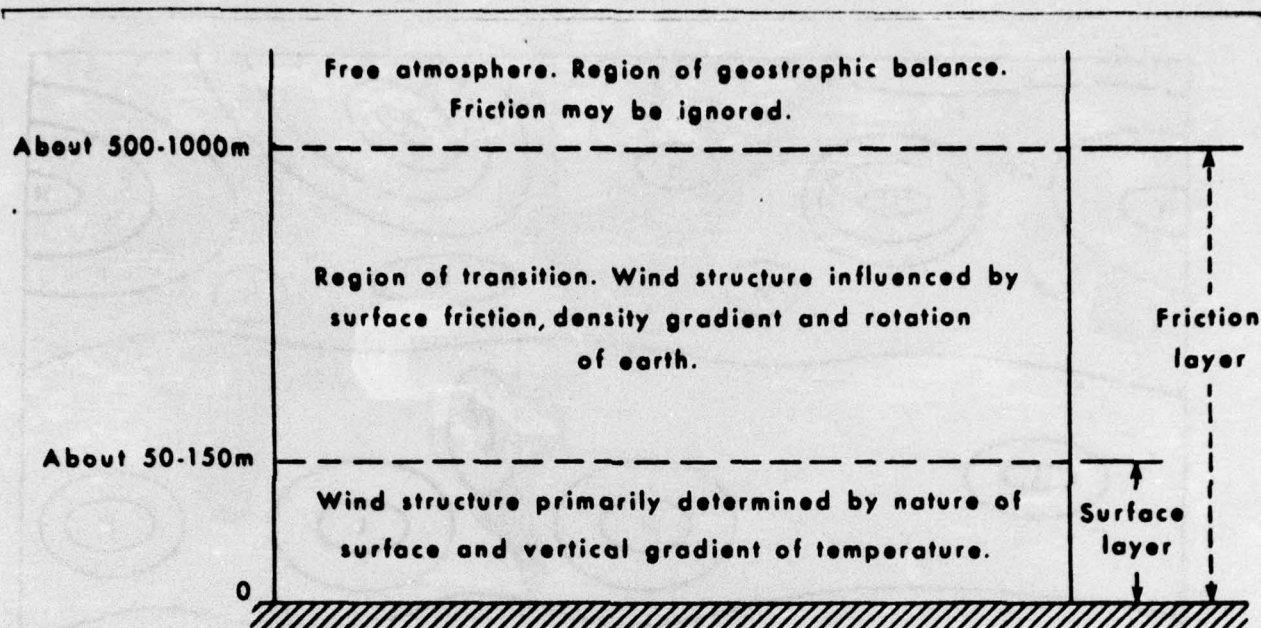
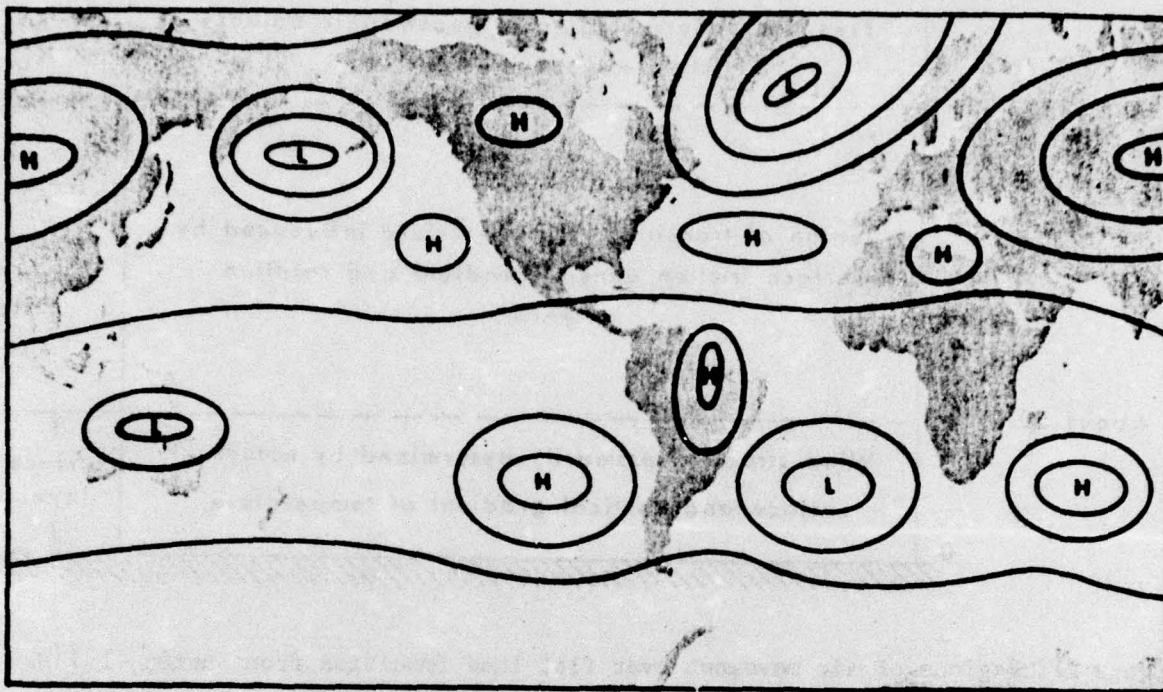


Figure 2. Regions of air movement over flat land (modified from Sutton, 1953).

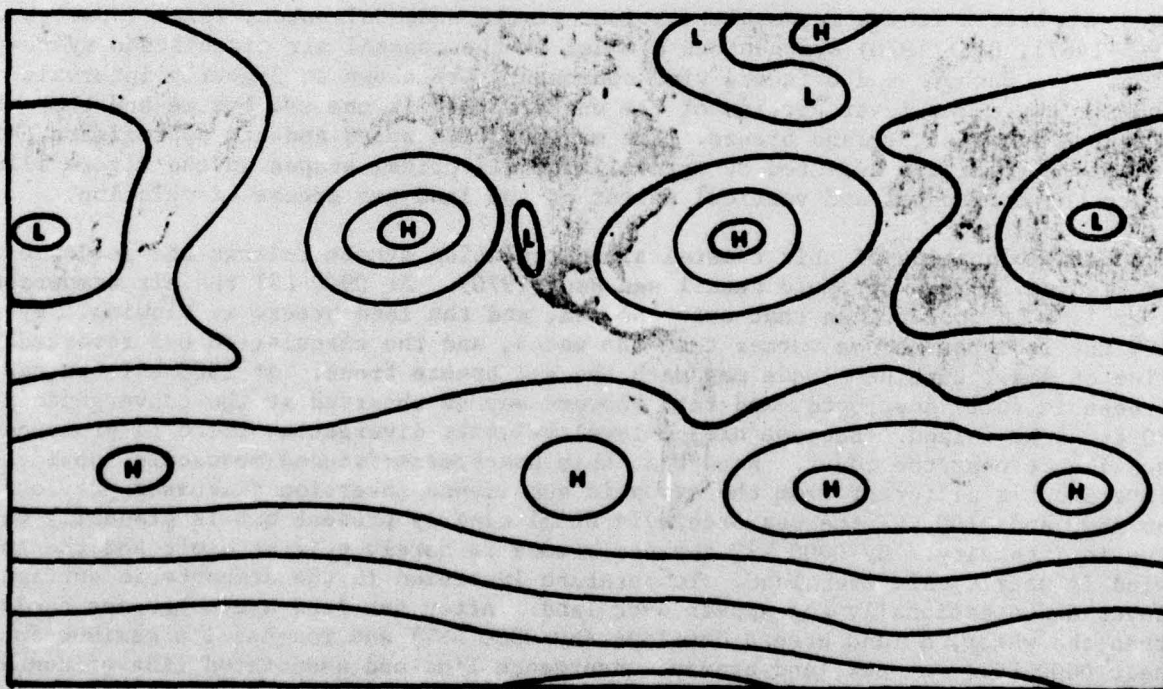
land-sea breeze from a mesoscale station network near Galveston, Texas (summers of 1965-1967), Hsu (1970) synthesized a model of the coastal air circulation system (Fig. 5). Onshore and offshore wind components are shown at 3-hourly intervals during the day. The lower portion of the onshore flow is the sea breeze and that of the offshore flow is the land breeze. The maximum wind speed and its approximate height in each current are depicted by arrows. The elliptical shapes in the figure illustrate the horizontal and vertical extent of the land-sea breeze circulation.

A brief explanation of this coastal air-circulation system follows the sequence shown in Figures 5a-5h. For more detail see Hsu (1970). At 0900 LST the air temperature over land is cooler than that over the sea, and the land breeze is blowing. By 1200 LST the land has become warmer than the water, and the circulation has reversed. A line of small cumulus clouds may mark the sea breeze front. At 1500 LST the sea breeze is fully developed, and rain showers may be observed at the convergence zone, 30 to 40 km inland. Because of low-level velocity divergence, there is pronounced subsidence near the coast. Note that this sea-breeze-induced mesoscale subsidence inversion is different from the synoptic subsidence inversion discussed previously. At 1800 and 2100 LST the sea breeze is still clearly present but is gradually weakening in intensity. By 0000 LST the sea breeze is barely evident aloft and the surface wind is nearly calm over land. Temperature inversion in the atmospheric surface layer and occasionally fog appear over land. After the land again becomes cooler than the water, a land breeze develops (by 0300 LST) and reaches its maximum intensity near 0600 LST. A weak land breeze convergence line and associated line of cumulus clouds develop offshore near sunrise. The land breeze continues until midmorning, when the sea-breeze cycle starts over.

Large lakes also are affected by pronounced land-sea breeze circulation. Figure 6 summarizes the various features associated with a typical lake breeze near the shore of Lake Michigan (Lyons and Olsson, 1973). The generalized streamlines of a well-developed circulation cell (Fig. 6A) are shown for a lake-breeze cell that has penetrated 15-20 km inland by midafternoon. Potential temperature patterns (Fig. 6B)



**Mean Pressure Pattern (January)**



**Mean Pressure Pattern (July)**

**Figure 3. Mean atmospheric pressure pattern for January (upper diagram) and July (lower).**



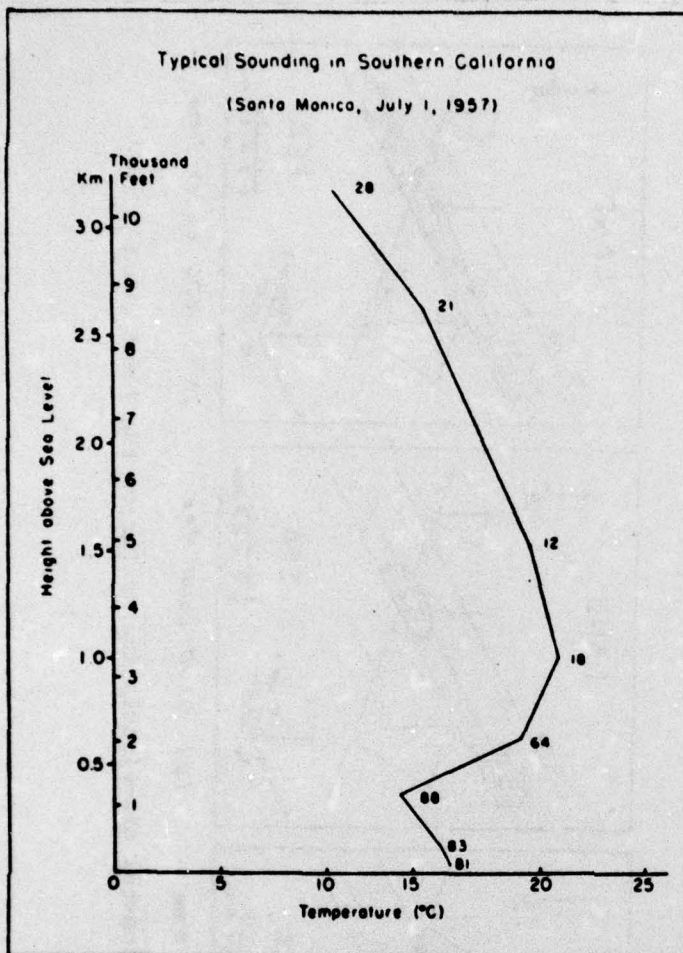


Figure 4. Example of temperature variation with height along the California coast showing the subtropical inversion (Neiburger, 1969).

usually reveal three inversion surfaces over the lake. The highest is a slightly depressed synoptic-scale subsidence inversion. A mesoscale subsidence inversion is found near the top of the inflowing layer, overlying a surface-based conduction inversion, the strength of which depends on the air-water temperature contrasts.

Because the internal boundary layer is important, it is treated in the next section. Smoke patterns associated with well-developed lake breezes are sketched in Figure 6C. Frequently, a wall of smoke marks the inland-rushing wind shift line, or the sea-breeze frontal zone. The trajectories of gases and various-sized aerosols are shown in Figure 6D. More research is required to determine the fraction of gases and particulates actually recirculated within the cell. This alternation of flow occurs also with sea and land breezes, which move air back and forth across the shoreline. For example, in Los Angeles (Neiburger, 1969) the air moved inland rapidly in the afternoon, slowed and reversed in the evening, and gradually moved inland the following morning. During its slow back-and-forth movement over the areas of heavy traffic and industrial activity, accumulation of high concentrations of pollution were observed (Neiburger, 1969).

Another important type of diurnal and local wind is the mountain and valley winds (see, e.g., Defant, 1951). The temperature difference between warm mountain slopes and air at the same altitude over nearby valleys causes air to rise along mountain slopes in the daytime. At night, reverse circulation occurs owing to radiational cooling of the earth's surface. These circulations are well developed on sunward-side slopes and weak or nonexistent on shady slopes. The thickness of the upslope wind layer is generally 100 to 200 m, and characteristic speeds are 2 to 4 m/sec. The nocturnal downslope wind is shallower and displays lower velocities.

Pronounced local diurnal circulations occur where land-sea breezes and upslope-downslope wind regimes reinforce each other. An excellent example of this reinforcement has been given by Flohn (1965) in studies of the Red Sea area, where steep escarpments rise abruptly a short distance from the coastline and generally fair skies allow maximum surface heating. Other places, such as those mentioned in Section 3.2,

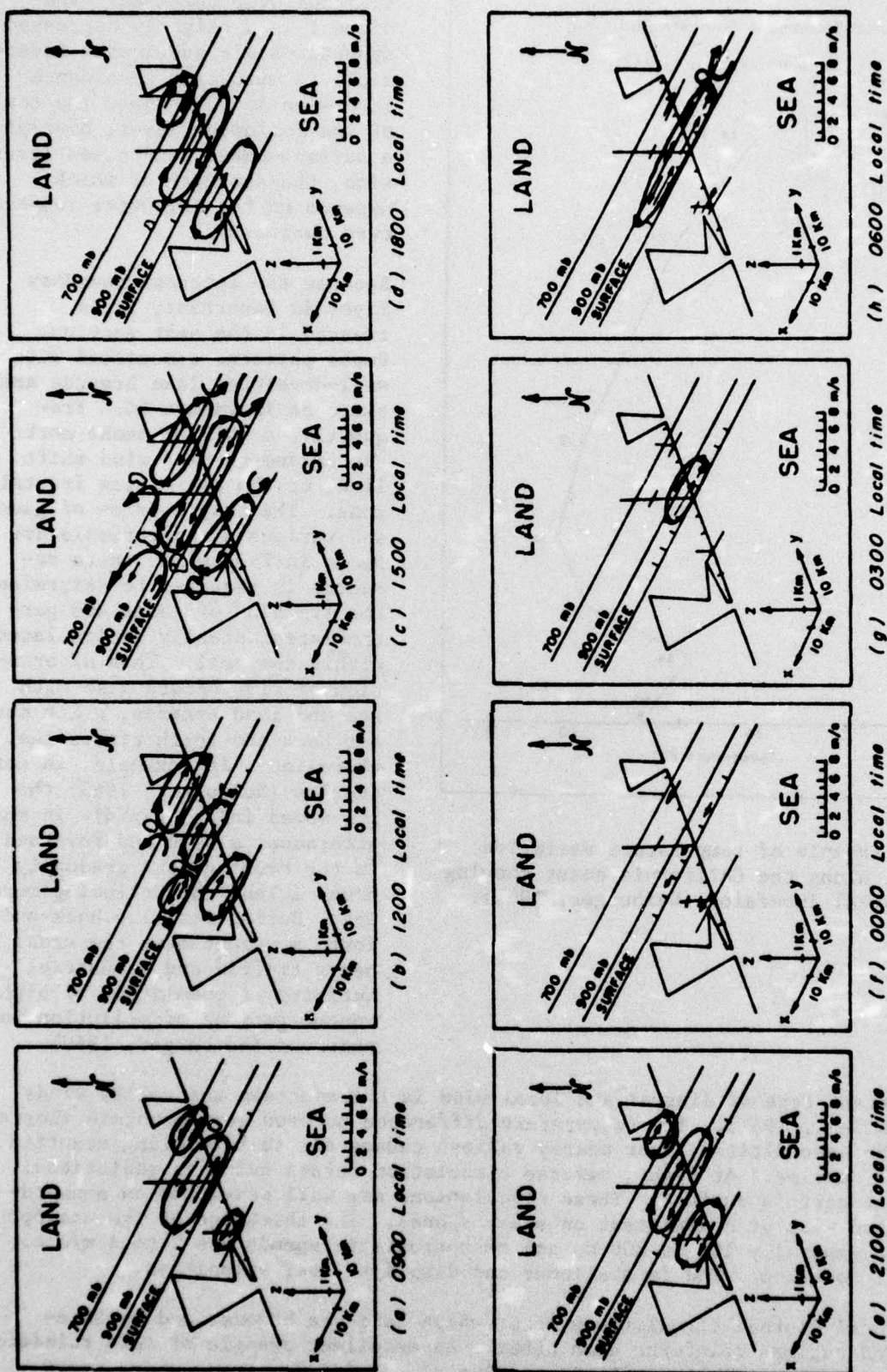


Figure 5. Synthesized empirical model of the coastal air-circulation system on the Texas coast between Galveston and Port Arthur (Hsu, 1970).



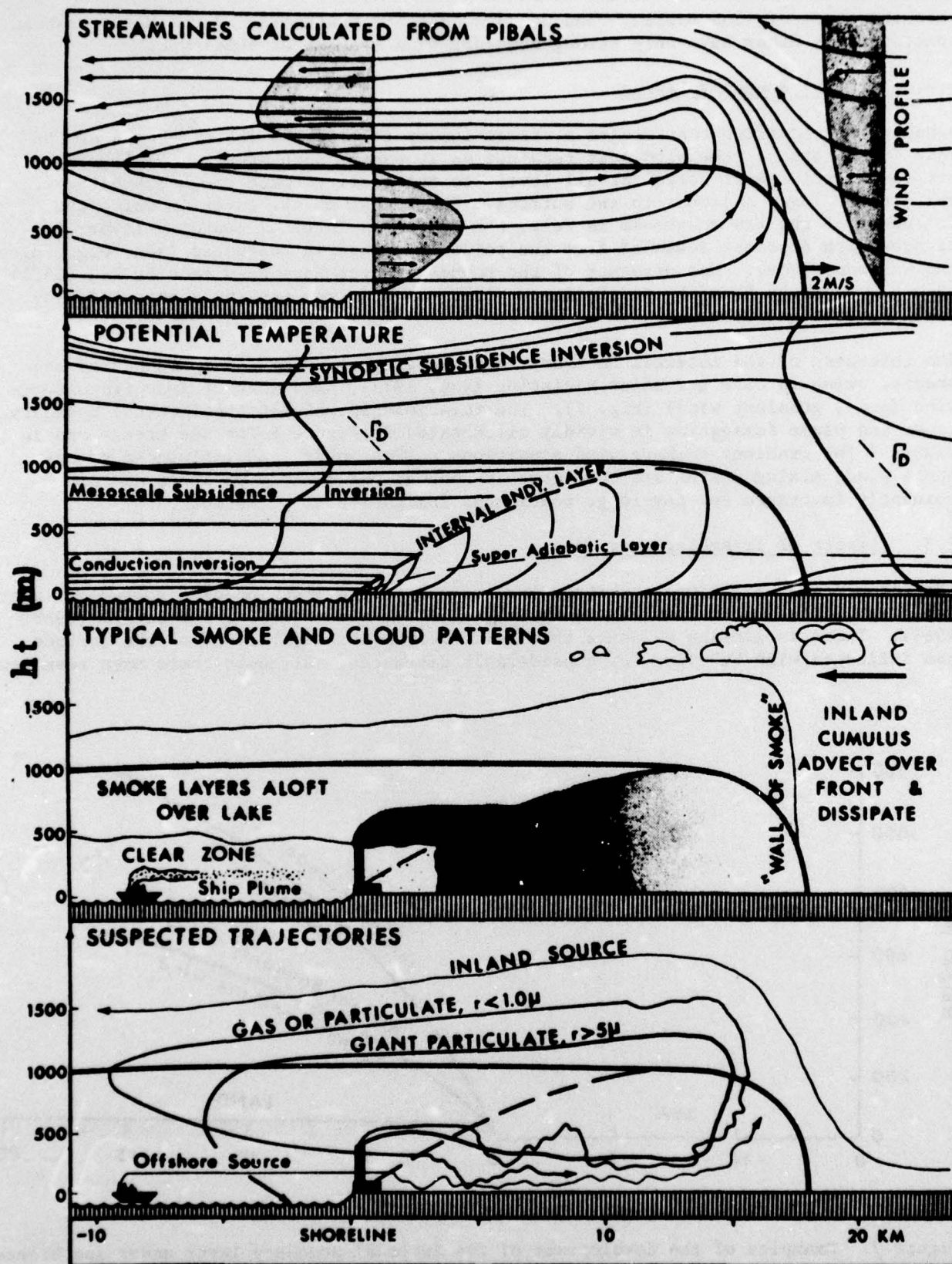


Figure 6. Summary of the (A) streamline, (B) potential temperature, (C) smoke and cloud, and (D) trajectory patterns associated with the typical land breeze near the shore of Lake Michigan (Lyons and Olsson, 1973).

have this type of wind system. The western coast of Guatemala and the Mediterranean coast of Asia Minor have very strong combined wind systems of this type.

### 3.4. Internal Boundary Layers

Because the coastline constitutes a discontinuity in terms of the roughness of the underlying surface, the wind must readjust as it passes such areas. The flow does not immediately adapt itself at all levels to the local surface roughness but does so only in the layer adjacent to the surface. The height of the layer in which the influence of the new roughness is felt, the so-called internal boundary layer, increases with distance downwind from the point of change in roughness (see, e.g., Blom and Wartena, 1969). Measurements of the boundary layer have been made by Hsu (1971) on a beach and by Panofsky and Peterson (1972) on a narrow peninsula surrounded by bays of varying widths.

The thickness of the internal boundary layer is greater under the influence of sea breeze, owing to stronger solar radiation (Hsu, 1973), than that of synoptic onshore wind (e.g., gradient wind) (Fig. 7). The relationship between the internal boundary layer and plume fumigation is vividly illustrated in Figure 6 for sea breeze and in Figure 8 for gradient onshore wind conditions. Thus, over land influenced by onshore wind, mixing depths are considerably reduced but greatly variable and are eminently favorable for day-long, continuous fumigation of pollutants.

### 3.5. Effects of Irregular Terrain

The influence of buildings and irregular terrain on the behavior of airborne effluents has been delineated to some extent by Smith (1968), Slade (1968), and Scorer (1958, 1968). There is growing evidence that relatively minor undulations of the surface can influence wind behavior for considerable distances. Although there have been few

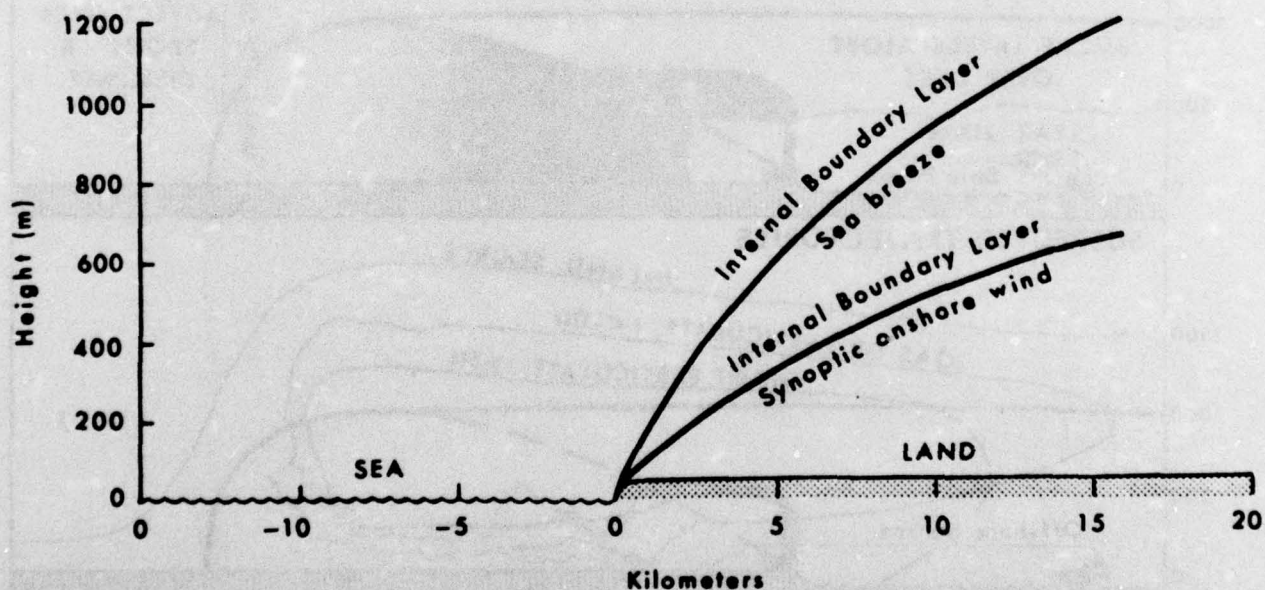


Figure 7. Examples of the development of the internal boundary layer under sea breeze and synoptic onshore wind influences on the shore of Lake Michigan (Lyons and Olsson, 1973; Lyons and Cole, 1973).



quantitative diffusion experiments over irregular terrain, visual observations of plume behavior in a variety of situations have been made.

The most important effect of irregular terrain is the separation of airflow on cliffs and mountains. Figure 9 shows that at the foot of a cliff facing the wind the airflow diverges, and an eddy may be formed there. The flow rejoins on the cliff face. The cliff top often behaves as a salient edge and an eddy extends varying distances downwind according to wind strength, gustiness, and stability. Separation may occur at many places on a hill of complicated shape, so that eddies, shed and unshed, of many different sizes may occur in its lee. As a result, the effluent of a chimney situated below the cliff is carried quickly to the ground if the chimney is in the wake (Fig. 10).

### 3.6. Other Considerations

In addition to dispersion characteristics, atmospheric stability is also important. Wind, stability, solar radiation, and cloud cover form the weather conditions which affect dispersion. According to Roll (1965), Kraus (1972), and Hsu (1974), offshore weather conditions related to diffusion may be classified into three categories:

- Condition 1 (daytime): Wind speed  $\leq 5$  m/sec and cloud cover  $\leq 3/8$  cloudiness;  
Condition 2 (day and night): Wind speed  $\leq 5$  m/sec, cloud cover  $\geq 4/8$  cloudiness;  
Wind speed  $> 5$  m/sec, disregard cloud cover;  
Condition 3 (nighttime): Wind speed  $\leq 5$  m/sec and cloud cover  $\leq 3/8$  cloudiness.

Note that conditions 1, 2, and 3 are equivalent to the overland Pasquill stability categories C, D, and E, respectively (e.g., Slade, 1968). Figure 11 shows the relationship between this classification and effective emission height in order to estimate the distance from an elevated source to the point of maximum ground-level

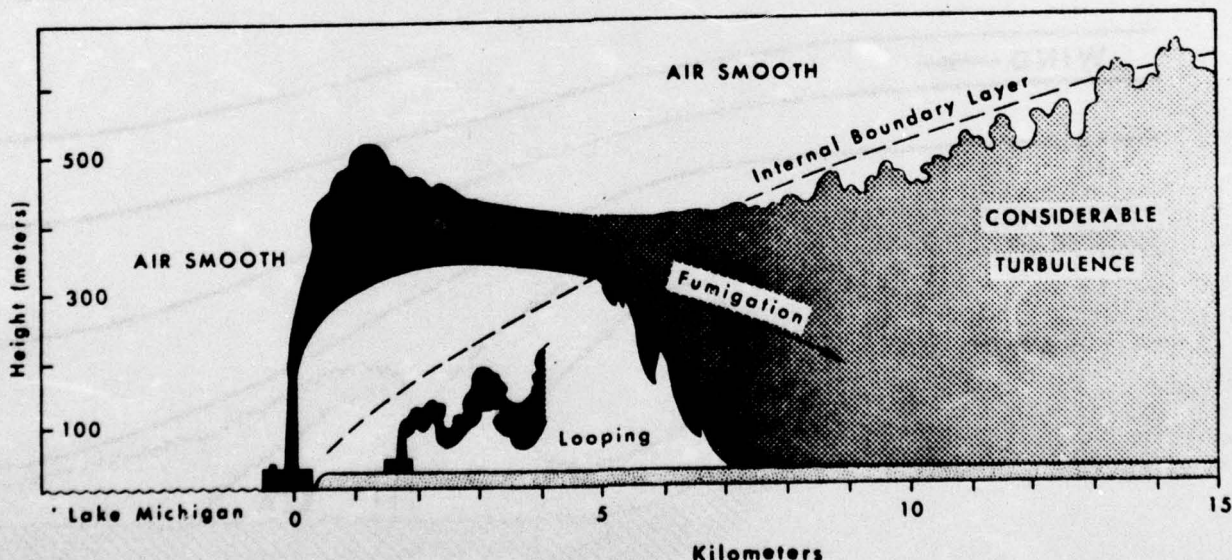


Figure 8. The relationship between internal boundary layer and plume fumigation under gradient onshore wind condition (Lyons and Cole, 1973).

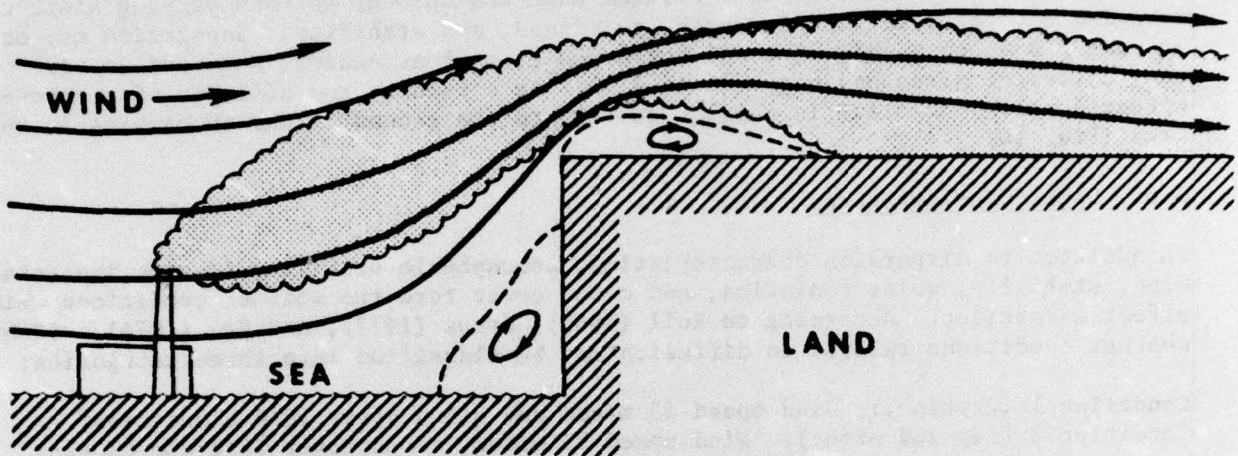


Figure 9. Plume dispersion on a windward cliffy coast.

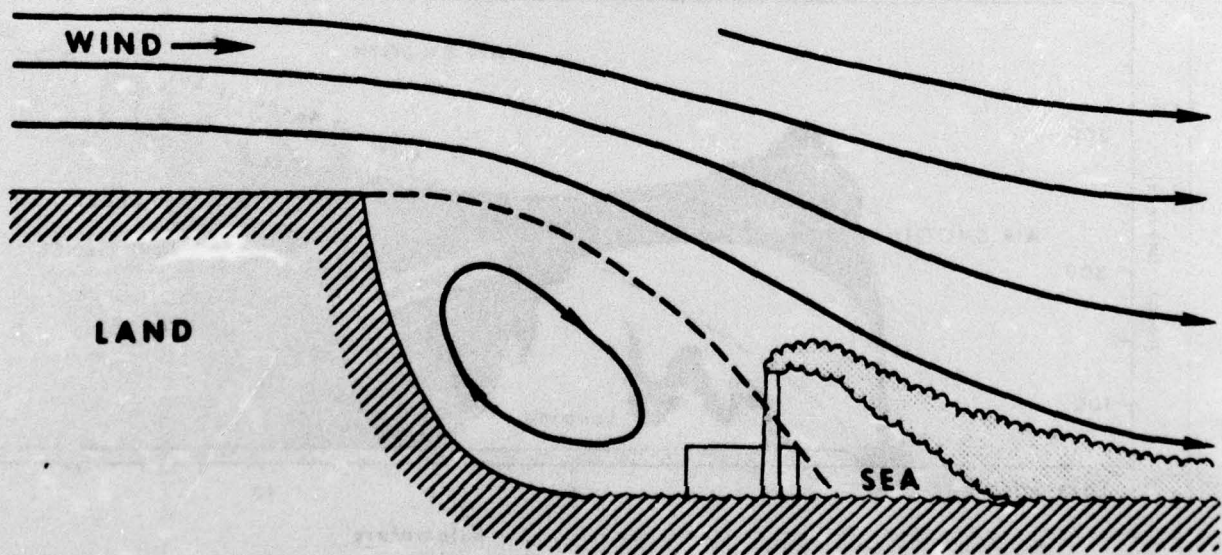


Figure 10. Plume dispersion on the leeward side of a cliffy coast.



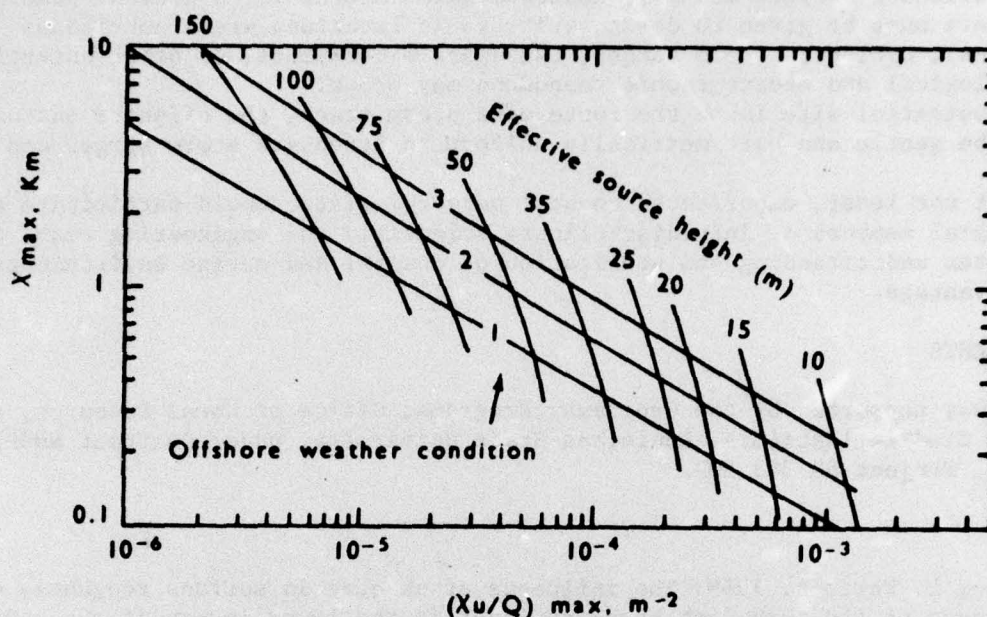


Figure 11. Distance from an elevated continuous source to point of maximum ground-level average concentration,  $x_{max}$ , and value of maximum ground-level concentration for various effective source heights and offshore weather conditions (modified from Martin, 1965) for offshore operations.

concentration,  $x_{max}$ , and values of maximum ground-level concentration. This calculation was made by proper analytical arrangement of Eq. (1). Figure 11 may be used as a guide for various offshore operations such as waste burning by an incinerator ship or oil-well burning resulting from an accident.

#### 4. SUMMARY AND RECOMMENDATIONS

For a given region where potential sites for offshore power plants and other structures are located, along with other considerations such as geology, economics, availability of cooling water, etc., proper measurement of pertinent meteorological conditions should be made. The measurement program should include all micro-, meso-, and synoptic-scales because of their varying temporal and spatial ranges. Specifically, places where there is pronounced diurnal coastal air circulation should be avoided. On the basis of the items discussed in Section 3, it is possible to select an area where those adverse effects are minimal. Some criteria are recommended as follows:

- (1) Offshore winds should be prevalent during most of the year, particularly during the summer.
- (2) The upwind coastal region should be relatively flat in order to avoid the terrain-induced vortex.
- (3) If there is an irregular terrain located upwind, the plant should be located downwind offshore at a distance at least 100 times the height of the terrain.
- (4) It is possible to design breakwater systems around the plant structure so that most pollutants will be trapped in these artificially created turbulent vortices before they reach the shore.
- (5) Nomographs similar to that in Figure 11 should be developed for the line source

- for an offshore airport and instantaneous point source for a nuclear-power plant.
- (6) Extra care must be given to design criteria in locations where hurricanes (typhoons), cyclones, storm surges, tsunamis, waterspouts, or other catastrophic meteorological and oceanographic phenomena may occur.
  - (7) If the potential site is on the route of a storm track, the offshore bottom slope should be gentle and bathymetrically uniform to attenuate storm surges and wave effects.
  - (8) Last but not least, experienced coastal meteorologists should participate actively as integral members of interdisciplinary scientific and engineering teams striving for better understanding and utilization of coastal and marine environments to best advantage.

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13. ABSTRACT <p>Proposed construction of offshore facilities such as nuclear-power plants, airports, and other structures which are potential emitters of pollutants necessitate consideration of atmospheric diffusion and analysis of the feasibility of such structures from the meteorological point of view. The potentially harmful nature of the radioactive materials involved dictates that even small quantities be treated with respect. Special attention must be given to design criteria in locations where hurricanes (typhoons), storm surges, tsunamis, waterspouts, or other catastrophic meteorological and oceanographic phenomena may occur.</p> <p>The movement of air pollutants is governed primarily by wind systems. In coastal zones influenced by land- and sea-breeze systems, at least two inversion layers exist: the mesoscale subsidence inversion and inversion associated with the internal boundary layer. Under onshore wind conditions (whether sea breeze or general gradient winds), an internal boundary layer occurs in the coastal zone owing to aerodynamic roughness as the wind crosses the sea and land interface. Therefore, plume trapping in the coastal boundary layer during onshore winds is pronounced and causes serious degradation of air quality. Thus, from an air-pollution point of view, there is no advantage to locating a power plant or similar structure offshore because onshore airflow will bring the pollutants to the coast. Furthermore, serious consideration should be given to site selection in coastal regions located east of the subtropical high-pressure region centered between 30° and 40° latitude because subsiding air produces inversions and light winds in addition to sea breeze effects. Cities in such areas are in the worst possible locations from the standpoint of vulnerability to pollution. Location of plants in these coastal areas should by all means be avoided.</p> <p>Nevertheless, there are some areas along continental and island coasts which may be suitable for power plant or airport location. Major criteria are the following: (1) Offshore winds should be prevalent during most of the year, particularly during the summer; (2) the upwind coastal region should be relatively flat in order to avoid a mesoscale turbulent vortex; (3) offshore bottom slope should be gentle and bathymetrically uniform to attenuate storm surges and minimize wave effects.</p>			

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